## Advanced Characterization Techniques
## Room Bansal Atrium - Session AC-MoP

## Advanced Characterization Techniques Poster Session I

**AC-MoP-1 Photoluminescence Mapping of Gallium Oxide***, **Matthew McCluskey,*** Washington State University

Photoluminescence (PL) spectroscopy is an important method to characterize dopants and defects in gallium oxide. Common features in the PL spectrum include the intrinsic UV band, blue and green bands that involve donor-acceptor pairs, and red emission due to $Cr^{3+}$ impurities. PL mapping with excitation wavelengths ranging from 266 to 532 nm reveals the spatial distribution of these features with micron resolution. Damage due to high-intensity laser pulses results in significant changes in the intensity and energy of the UV band. In Czochralski-grown $\beta$-$Ga_2O_3$:Fe, the $Cr^{3+}$ emission intensity shows striations that are attributed due to inhomogeneities during growth. In addition to defects in the bulk, PL microscopy has revealed several specific defects on the surface. Some of these localized centers are very bright UV emitters. Raman scans of these bright emitters revealed hydrocarbon peaks, which may point toward the origin of the light emission.

**AC-MoP-2 Linearly Polarized UV, Blue, and IR Photoluminescence from β-$Ga_2O_3$***, J. Cooke, M. Lou,* ***Michael Scarpulla,*** University of Utah*; A. Bhattacharyya,* University of California, Santa Barbara*; X. Cheng, Y. Wang,* University of Utah*; S. Krishnamoorthy,* University of California, Santa Barbara*; B. Sensale-Rodriguez,* University of Utah

An ultra-wide bandgap of 4.8 eV makes b-$Ga_2O_3$ a promising material for power devices and ultra-violet (UV) optoelectronics such as UV-transparent electrodes and solar-blind photodetectors. It is well-known that the optical absorption of b-$Ga_2O_3$ is anisotropic, having different threshold energies for different incident linear polarizations. Due to its low symmetry, the polarization of the emitted photoluminescence (PL) of b-$Ga_2O_3$ should also be polarized; but this phenomenon which could allow distinguishing between point defects based on their structure has received much less attention. Polarized emission has been predicted and measured to be strongly related to self-trapped holes (STHs) involving O displacements, impurities, and doping. The reported typical b-$Ga_2O_3$ PL is composed of UV, blue, green, and red main emission bands. Previously-reported PL has discussed excitation polarization-dependent PL, but there has been no discussion of polarized PL emission which we have found also to be polarization dependent.

Herein we report the emission polarization dependence of various high-crystalline-quality melt-grown bulk b-$Ga_2O_3$samples. It was found that (

We also observed polarized emission for Fe-doped bulk b-$Ga_2O_3$ samples. Both the b-orientation and [102]-orientation showed red PL with different intensities. Whereas UV, blue, and green PL in UID and Sn-doped samples come from band transition recombination, red PL in Fe-doped samples comes from $Cr^{3+}$. Therefore, the causes of this emission polarization dependence are different, potentially caused by orbitals within the $Cr^{3+}$.

**AC-MoP-3 Non-Uniformity and Hysteresis of Capacitance-Voltage Doping Profiling in B-$Ga_2O_3$***, **Jian Li**, A. Charnas, B. Noesges, A. Neal, T. Asel, Y. Kim, S. Mou,* Air Force Research Laboratory, Materials and Manufacturing Directorate, USA

Doping and defects – the important aspects of b-Ga2O3 technology development – are entangled in both their underlying physics and their electrical characterization. Doping uniformity is expected to be key to the feasibility and yield of larger-scale manufacturing of b-Ga2O3-based electronics. This work is concerned with vertical doping uniformity, which is closely tied to present-day challenges such out diffusion of compensating impurities (e.g., Fe and Mg) and interfacial accumulation of doping impurities (e.g., Si). The capacitance-voltage(CV) measured doping profiles of b-Ga2O3 materials by this work and others often show a non-uniformity varying from 15% to 140% over the depth of 100s of nm. The ubiquity of this observation and its indifference of the growth and doping methods are inexplicable from sheer growth point of view therefore warrant a close scrutiny.

The apparent doping profile non-uniformity in a Schottky junction may be accompanied by the observation of CV hysteresis, which shares a common electrostatic basis underlying the threshold voltage instability in field-effect transistors. Irmscher et al. in 2013 reported CV hysteresis in a b-Ga2O3 Schottky diode without accompanying analysis but the subject of that report was on deep levels therefore hinting their implicit role in CV hysteresis. Indeed, works in earlier decades have proven deep states as the origin of CV hysteresis, which manifests the difference of equilibrium and non-equilibrium CV scans. To date, defects in b-Ga2O3 have been detected and characterized by Hall, DLTS, and its variants such as DLOS and admittance spectroscopy. This work explores the case of using illumination-less steady-state room-temperature CV technique for dual-purpose investigation of doping and defect in b-Ga2O3.

We investigate the relationship between doping non-uniformity and carrier dynamics in deep levels in b-Ga2O3. We speculate that the carrier density non-uniformity is in part contributed by an artifact due to carrier emission from deep levels and seek experimental evidences from analytical electrostatic modeling of hysteresis observed in cyclic CV measurements. We aim to separate the contributions of doping and deep levels to more accurately quantify their respective parameters, i.e., doping density and spatial distribution for the former, and energy, density, and capture cross-section for the latter. The materials under investigation include bulk substrates and MBE and MOCVD grown epitaxial layers. We will discuss the implication of our findings on MOSFET operation for power electronic applications.

**AC-MoP-4 Scanning Transmission Electron Microscopy (S/TEM) Investigation of γ-$Ga_2O_3$ Defective Layers In Aluminum and Scandium Alloyed β-$Ga_2O_3$***, **Andrew Balog,*** The Pennsylvania State University*; A. Chmielewski,* CEMES-CNRS, France*; R. Lavelle, L. Miao,* The Pennsylvania State University*; J. Jesenovec, B. Dutton,* Washington State University*; C. Lee, E. Ertekin,* University of Illinois at Urbana Champaign*; J. McCloy,* Washington State University*; N. Alem,* The Pennsylvania State University

Beta gallium oxide (β-$Ga_2O_3$) has gained interest recently as an attractive candidate for high power electronics and extreme environment applications. Possessing a monoclinic structure (space group C2/m), the anisotropic unit cell creates a unique combination of properties. Most important among these is a band gap around 4.8 eV, 1.4 eV greater than the most widely studied UWBG semiconductor, GaN. This results from the presence of tetrahedral and octahedral gallium sites, as well as three inequivalently coordinated oxygen sites. β-$Ga_2O_3$ suffers from a low thermal conductivity an order of magnitude below common UWBG and power semiconductor materials, as well as a lack of achievable p-type doping. However, the material's most fundamental constraint is insufficient knowledge about defect formation, behavior, and their impact on properties. Recent attempts at alloying β-$Ga_2O_3$ with scandium and aluminum shows promise mainly in increasing β-$Ga_2O_3$'s band gap, as the monoclinic phases of $Sc_2O_3$ and $Al_2O_3$ demonstrate increases up to 5.48 eV and 7.24 eV, respectively. Increasing the band gap via alloying is vital for producing devices in higher critical field applications. However, the role these elements play in defect formation is still not well understood.

Using Scanning/Transmission Electron Microscopy (S/TEM) imaging and spectroscopy, we study how the addition of scandium and aluminum can change the atomic and electronic structure of β-$Ga_2O_3$. In addition, we identify a nanometer-scale layer of γ-$Ga_2O_3$ at the surface of a Czochralski-grown single-crystal of β-$Ga_2O_3$. S/TEM and the suite of tools it provides such as electron energy loss spectroscopy (EELS) and energy dispersive spectroscopy (EDS), also allows for probing local electronic states around defects and general compositional mapping. This provides further information on the environment around defects and their impact on local structure. Using S/TEM imaging we investigate how the γ polymorph of $Ga_2O_3$ forms as a thin film on the surface of β-$Ga_2O_3$, while the local bonding environment is uncovered by studying variations in the oxygen EELS K edge. Understanding the formation and structure of this defect phase is vital for improvement of processing and growth techniques, while also allowing for the study of the role alloys play in the defect formation process.

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